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Verification and Validation of the STAT7 Code

Nuclear Engineering Division

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Verification and Validation of the STAT7 Code

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Abstract

This document presents the verification and validation of the STAT7 Version 1.0 code which has been developed to perform the steady-state thermal hydraulic safety calculation of the MIT Research Reactor required upon conversion of the reactor from high enrichment uranium fuel to low enrichment uranium fuel.

The key capabilities of the code including the statistical processing, water property generation, and thermal hydraulic solution are verified independently. While the first two capabilities are checked using statistical tests and NIST data tables, each component of the thermal hydraulic solution is verified using simple geometry test problems. The comparison between results obtained by the code and hand calculations on these problems shows that each of these components work correctly.

Additionally, a comprehensive comparison between STAT7 Version 1.0 and PLTEMP/ANL_4.2 calculations for a five-channel test problem is performed for the validation. The good agreement between the obtained results for all thermal hydraulic parameters belonging to the fuel core region is achieved. An issue in bypass flowrate calculation was detected when both fin-friction and bypass flow calculations are involved. This problem can be corrected in a later version of the code, however, does not affect the application of STAT7 code as it has been used to date where the flow distribution in the core region and bypass channel is specified as an input parameter.

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1 Introduction

The STAT7 Version 1.0 code was written to automate many of the steady-state thermal hydraulic safety calculations for the MIT research reactor [Ref. 1]. A Monte-Carlo statistical propagation approach is used to treat uncertainties in important parameters in the analysis. In these safety calculations, the limiting safety settings are based on avoiding onset of nucleate boiling (ONB).

This document presents the verification of STAT7 code through the following steps:

- (1) The statistical capability is evaluated by checking the random number generator embedded in the code. The MATLAB software is used to rebuild this generator and to test the randomness of the generated numbers.
- (2) The fit functions used by the code to generate coolant properties are checked by comparing the obtained data with those presented in the National Institute of Standards and Technology (NIST) tables [Ref. 2].
- (3) The key capabilities of thermal hydraulic (TH) solution are verified independently by comparing between the code and hand calculations of a simple geometry test problem without the statistical sampling. The test problem is modified into the test cases to consider the code's capabilities: basic thermal hydraulic calculation; bypass flow; end-channel treatment, fin option; effects of viscosity on flow rate; power split; and ONB temperature.
- (4) A comprehensive comparison between STAT7 Version 1.0 and PLTEMPANL_4.2_r80_160720 [Ref. 3] calculations using a five-channel test problem with finned fuel plates is performed.

The separation of the thermal hydraulics capabilities in (3) is to avoid the situation in which the errors caused by two or more capabilities compensate to each other, while the comprehensive comparison in (4) is to confirm that all these capabilities can work together correctly.

2 STAT7 Overview

The main structure of STAT7 is presented in Figure 1. Beside the statistical sampling and processing, the remaining important part is the thermal hydraulic solution embedded in the subroutine THYDRL. All of the code's capabilities are briefly described in Table 1.

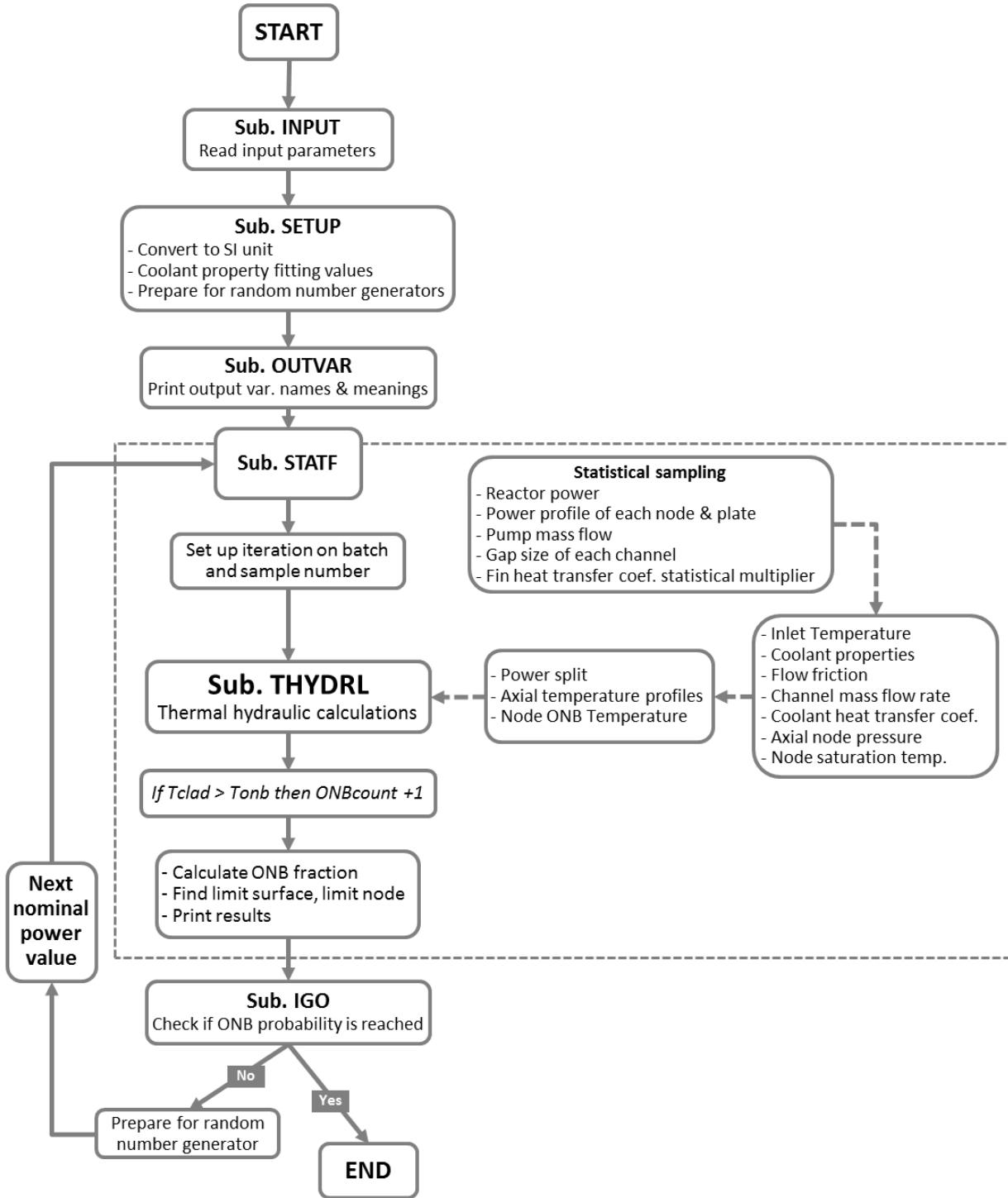


Figure 1. Main structure of the STAT7 Code.

Table 1. STAT7 code's capabilities

No.	Capabilities	Description
1	Statistical sampling	Generation of random numbers for statistical sampling process
2	Water property	Generation of water properties using embedded fit functions
3A	Basic TH calculation	Basic TH calculation
3B	Bypass option	TH calculation with the present of bypass channel
3C	End-channel treatment	TH calculation with different boundary conditions of end-channel
3D	Fin option	TH calculation with the existence of fins on fuel cladding surfaces
3E	Viscosity effect	TH calculation considering the effect of viscosity on flowrate
3F	Power split	TH calculation taking the asymmetry power split into account
3G	ONB Temperature	Checking node's surface temperature against the ONB limit

3 Verification Approach and Test Problems

3.1 Statistical processing

The random number generator embedded in the code is checked using two statistical tests including Chi-squared and Runs tests. The MATLAB's commands are used to rebuild this generator and to check the generated set of numbers against these tests.

3.2 Water properties

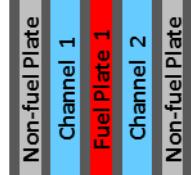
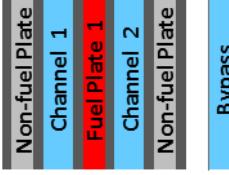
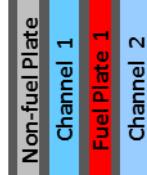
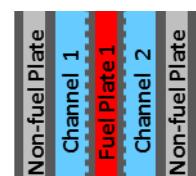
The verification of the fit functions used by the code to generate coolant properties including density, specific heat capacity, viscosity, and saturation temperature are performed by comparing the obtained parameters with the data presented in the NIST tables. As will be seen in the Section 4.2, the data predicted by the code agree well with those on the NIST tables. Therefore, for the convenience, the hand calculation of thermal hydraulics will use these fit functions to determine coolant properties.

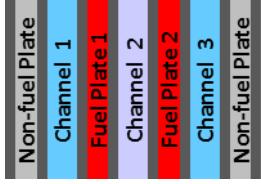
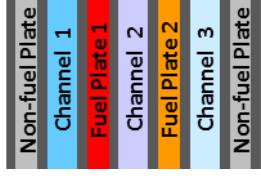
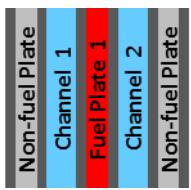
3.3 Key thermal hydraulic capabilities

For the verification of the thermal hydraulic solution, both code and hand calculations use the nominal data (without the statistical sampling). Simple geometry test problem of two channels are set up and then modified to form test cases to consider the code's key capabilities separately. Several assumptions are applied in each test case to isolate one key capability from others. For example, during the consideration of the fin-option, the effects of viscosity on the channel flow rates are assumed ignorable. Accordingly, the code's control options are specified in the input desk to focus on the key capability under considered. The summary of the thermal hydraulic verification approach are presented in Table 2.

It should be noticed that if the equal power split assumption is used in the cases of non-identical channels (cases C and E), the peak fuel temperature obtained for the left and right sides of the fuel plate will be different from each other. Although this is physically unreasonable, the code and hand calculation still employ the assumption to separate the power split calculation from other capabilities.

Table 2. Verification approach for thermal hydraulic capabilities

Capabilities	STAT7 Version 1.0 test model	Hand calculation scheme	Geometry description
3A. Basic thermal hydraulic calculation	<p>Set up base model:</p> <ul style="list-style-type: none"> - Two identical channels - One fuel plate with constant power density - Use adiabatic boundary condition with non-fuel plates. - Zero fin height - Ignore viscosity effect on flow rate - No bypass - Use nominal values 	<ul style="list-style-type: none"> - Determine geometry parameters - Calculate inlet temperature from outlet temp., core flow rate, and core power - Channel flow rate = $0.5 \times$ core flow rate - Use equal power split (symmetry) to get channel power and heat flux at the surface - Get coolant temperature profiles and coolant properties - Get friction factor and pressure drop for each axial node - Get axial temperature profiles and ONB temp. - Get heat transfer coefficients. 	<ul style="list-style-type: none"> - Five axial nodes - Three stripes - Upward flow <p>Cross-section:</p> 
3B. Bypass option	<p>Modify the base model:</p> <ul style="list-style-type: none"> - Add bypass flow with the same hydraulic diameter as in the channel - Increase pump flow 	<ul style="list-style-type: none"> - Core flow rate = Core flow area \times Total flow rate / (Core flow area + Bypass flow area) - Repeat (A) 	
3C. End-channel treatment	<p>Modify the base model:</p> <ul style="list-style-type: none"> - Remove 3rd plate by setting IENDN = 0 - Use equal power split (ioptn2=1) 	<ul style="list-style-type: none"> - Determine geometry parameters - Calculate channel frictions and channel flow rates - Repeat (A) 	
3D. Fin option	<p>Modify the base model:</p> <ul style="list-style-type: none"> - Add fins 	<ul style="list-style-type: none"> - Determine geometry parameters with the present of the fins - Repeat (A) using Carnavos correlation of heat transfer at clad surface 	

Capabilities	STAT7 Version 1.0 test model	Hand calculation scheme	Geometry description
3E. Viscosity effect on flow rate	Modify the base model: <ul style="list-style-type: none"> - Add one channel and one fuel plate - Remove Oxide & Zr layers - Use viscosity effect - Use equal power split 	<ul style="list-style-type: none"> - Calculate inlet temperature - Two-step iteration to get outlet temperature, average temperature, average viscosity, and flow rate for each channel. - Repeat (A) 	
3F. Power split	Modify the model of (E): <ul style="list-style-type: none"> - Use different plate powers - Turn on the power split calculation - Ignore viscosity effect on flow rate 	<ul style="list-style-type: none"> - Channel flow rate = $1/3 \times$ core flow rate - Use power split of 0.5/0.5 for the first axial nodes - Two-step iteration to get temperatures, coolant properties, power split and other parameters (from the first to last nodes). 	
3G. ONB Temperature	Modify the base model: <ul style="list-style-type: none"> - Increase core power until ONB occurs. 	<ul style="list-style-type: none"> - Repeat (A) - List out the nodes at which clad surface temperature > ONB temperature 	

3.4 STAT7 and PLTEMP comparison

It should be noticed that STAT7 provides two options for the calculations of the flow friction at the end channel with fins at one side: (1) using Carnavos correlation and (2) taking average of the finned and smooth friction factors as in PLTEMP_4.2_r80_160720. The option (2) will be used for the comparison between the codes.

A test problem of five channels and four finned fuel plates in which the end-channels have fins at one side is set up for the comparison purpose. To obtain the comparable models of STAT7 and PLTEMP, the following different input specifications of the codes need to be handled during the preparation of input data:

- (a) **Fin geometry description:** STAT7 uses groove depth, groove width, and width of groove tip to specify the series of fins placed continuously on the clad surface. PLTEMP requires the data of fin height (groove depth), fin width (width of groove tip) and total number of fins in channel. Hence, the number of fins on one clad surface needed for PLTEMP is calculated by:

$$\text{Number of fins} = \text{Plate width} / (\text{Groove width} + \text{Width of groove tip})$$

- (b) **Specified temperature and pressure:** STAT7 designed for MIT Reactor requires the outlet temperature and pressure to be specified, while PLTEMP uses inlet temperature and pressure as the input data. Therefore, the STAT7 model needs to be built and run first. The obtained inlet temperature and pressure will be used as the input of PLTEMP model. The comparison between the codes will consider the temperatures of coolant, clad, and fuel as well as pressure, heat flux, and heat transfer coefficients for all axial nodes and channels.
- (c) **Input flow rate:** the total coolant flow rate (including the core flow and bypass flow) can be defined in the input of STAT7 but PLTEMP requires the specification of flow rates in each channel or the total core flowrate if the search option is used. Therefore, the total core flow rates calculated by STAT7 is used for PLTEMP model to allow the code-to-code comparison.

The cross-section and specifications of the test problem are presented in Figure 2 and Table 3, respectively. Both input decks of STAT7 and PLTEMP are given in Appendix 1.



Figure 2. Cross-section of the test problem geometry used for STAT7 and PLTEMP comparison

Table 3. Specifications of test problem

Group	Parameters	STAT7	PLTEMP
FUEL	Number of fuel assemblies	1	
	Number of fuel plates	4.0	
	Fuel length, m	1.0	
	Fuel width, m	0.4	
	Fuel thickness, m	0.01	
	Fuel thermal conductivity, W/mK	50.0	
	Clad thickness (one side), m	0.005	
	Clad thermal conductivity, W/mK	100.0	
FIN	Groove depth/Fin height, m	0.002	
	Width of groove tip/Fin width, m	0.002	
	Groove width, m	0.002	*
	Number of fins in an internal channel		200
COOLANT	Number of coolant channels	5	
	Left boundary of the first channel (#1)	Non-fuel plate	
	Right boundary of the last channel (#5)	No plate	
	Coolant channel thickness without the present of fins, m	0.02	
	Total flow rate, kg/s	30.0	
	Core flow rate, kg/s		24.577**
	Outlet temperature, °C	50.0	
	Inlet temperature, °C		34.05**
	Outlet pressure, Pa	101325	
	Inlet pressure, Pa		111300**
	Bypass flow area, m ²	0.005	
	Bypass hydraulic diameter, m		0.05
POWER	Total power (no deposition in clad and coolant), MW	2.0	
	Plate power / Core average power	Plate #1	0.4
		Plate #2	0.8
		Plate #3	1.2
		Plate #4	1.6
	Axial power distribution obtained from a same power correlation: - STAT7 uses node centers - PLTEMP uses node interfaces	Node 1 / Interface 1	0.063876
		Node 2 / Interface 2	0.077787
		Node 3 / Interface 3	0.089492
		Node 4 / Interface 4	0.09899
		Node 5 / Interface 5	0.106282
		Node 6 / Interface 6	0.111368
		Node 7 / Interface 7	0.114248
		Node 8 / Interface 8	0.114921
		Node 9 / Interface 9	0.113388
		Node 10 / Interface 10	0.109648
		Interface 11	0.099142

(*) Grayed cell indicates a value that is not required by the input deck.

(**) The value obtained by the STAT7 calculation that is used for PLTEMP model.

4 Results and Discussion

4.1 Statistical samplings

Using MATLAB commands, the random number generator embedded in the STAT7 code is rebuilt to generate a set of 200000 numbers. The MATLAB files developed to perform this task are located in the code repository for STAT7 under the verification-related directory. Two statistical tests including Chi-squared test and Runs test [Ref. 4] are considered.

(a) Chi-squared test for distribution

The generated numbers are grouped into 20 bins (degree of freedom is 19). Using the Chi-squared table, the critical values of two-tailed test and a 95% level of confidence are 8.85 and 32.91. The obtained value of χ^2 is

$$\chi^2(19, N = 200000) = 19.62, p < .05, \text{two-tailed}$$

Thus, this test indicates that the generated set of numbers has a uniform distribution.

(b) Runs test for randomness

By coding the numbers above the median as positive and numbers below the median as negative, a run can be defined as a series of consecutive positive or negative values. The number of runs, r , detected for the generated set of numbers is:

$$r = 99956$$

With n_1 and n_2 are the number, n , of positive and negative values in the series, respectively, the mean, μ_r , and standard deviation, σ_r of the runs are

$$\mu_r = \frac{2n_1 n_2}{n_1 + n_2} + 1 = 100000$$

$$\sigma_r = \frac{2n_1 n_2 (2n_1 n_2 - n_1 - n_2)}{(n_1 + n_2)^2 (n_1 + n_2 - 1)} = 223.6$$

The test statistic, z , is calculated by

$$z = \frac{r - \mu_r}{\sigma_r} = -0.201$$

Comparing to the critical values corresponding to 95% level of confidence $-1.96 < z < 1.96$, the test statistic is within this range, and therefore, it is concluded that the numbers are generated randomly.

4.2 Coolant properties

The coolant properties obtained using the fit functions embedded in the code and NIST tables for three different temperatures at 101325 Pa (the pressure at the top of MIT fuel core) are presented in Table 4. The saturation temperatures at different pressures are given in Table 5.

Table 4. Coolant properties

Temperature (°C)	Method	Density (kg/m ³)	Specific heat capacity (J/kg·K)	Thermal conductivity (W/mK)	Viscosity (Pa·s)
30	NIST table	995.65	4179.80	0.61550	7.9735E-04
	Fit function	995.66	4179.13	0.61552	7.9820E-04
	Relative difference, %	0.001	-0.016	0.003	0.107
60	NIST table	983.20	4185.00	0.65439	4.6640E-04
	Fit function	983.25	4184.45	0.65420	4.6621E-04
	Relative difference, %	0.005	-0.013	-0.028	-0.040
90	NIST table	965.31	4205.20	0.67527	3.1441E-04
	Fit function	965.34	4205.42	0.67539	3.1470E-04
	Relative difference, %	0.003	0.005	0.018	0.094

Table 5. Saturation temperature, °C

Method \ Pressure	101325 Pa	111325 Pa	121325 Pa
Fit function	99.974	102.630	105.100
NIST table	100.002	102.661	105.129
Relative difference, %	0.028	0.030	0.028

It can be seen that all the generated coolant properties for the working flow conditions of the MITR agree well with the values presented on NIST tables. The relative differences less than 0.11% for viscosity, and 0.03% for all other parameters, confirm that the fit functions embedded in the code can predict the properties correctly.

Based on these results, it is reasonable for the hand calculation subsequently described to employ these fit functions to get the necessary coolant properties.

4.3 Thermal hydraulic capabilities

This section presents the comparison between the data obtained by code and hand calculations for all test cases described in Table 2. The output variables are as the following:

jz	axial node
tcoola	node averaged coolant temperature, °C
tsata	saturation temperature, °C
reya	Re
vsca	viscosity, °C
rhocla	coolant density, kg/m ³
pcoola	pressure, Pa
cpta	specific heat capacity, J/kg·°C
acc	channel coolant flow area, cm ²

dh	channel hydraulic diameter, cm
whs	channel mass flowrate, kg/s
Tsurf	clad surface temperature, °C
Tox-cd	oxide-clad interface temperature, °C
Tcd-zr	clad-Zr interface temperature, °C
Tzr-f	Zr-fuel interface temperature, °C
Tfmax	peak fuel temperature, °C
Tcd-f	clad-fuel interface temperature (when oxide and Zr layers have been removed), °C
xkcp	film thermal conductivity, W/(mK)
prp4p	Pr ^{0.4} (used by heat transfer correlations)
hcool	film heat transfer coefficient, W/(m ² K)
qc	surface heat flux, W/cm ²
fp	power split (= heat flux at one side / sum of heat flux at both side)

The input and output files of these test cases as well as a MS Excel spreadsheet handling the hand calculation and data comparison are placed in the code repository for STAT7 under the verification-related directory.

The comparison between code and hand calculation in the symmetric two-channel cases (A, B, and D) will consider the thermal hydraulic parameters of channel #1 and the left side of the fuel plate #1. For the remaining cases, the comparison includes the channels #1 and #2 as well as both sides of the fuel plate #1. In the following tables, the hand calculation data are present in normal text, while the code results use **bold format**. Note that the first nonfuel plate of the model is named as Plate #1 in the output file and therefore, a fuel plate #n in Figure 1 or Figure 2 corresponds to the plate #(n+1) of the output. In addition, the output variables mentioned above are printed out in the output file with numbers 1 and 2 to indicate the left and right sides of the plate.

4.3.1 Capability 3A - Basic thermal hydraulic calculation

The obtained thermal hydraulic data of channel #1 and the left side of fuel plate #1 of this test case are presented in Table 6 and Table 7. The maximum relative difference between code and hand calculations of all parameters in this test case is 0.09%.

Table 6. Channel #1

jz	tcoola	tsata	reya	vsca	rhocol	pcool	cpa
1	47.31	104.79	69901.4	5.722E-4	989.41	120907	4179.91
	47.31	104.79	69900.0	5.722E-4	989.40	120900	4180.00
2	47.91	104.31	70626.4	5.664E-4	989.15	118923	4180.06
	47.91	104.31	70630.0	5.664E-4	989.20	118900	4180.00
3	48.50	103.82	71353.9	5.606E-4	988.89	116938	4180.21
	48.50	103.82	71350.0	5.606E-4	988.90	116900	4180.00
4	49.10	103.33	72083.9	5.549E-4	988.63	114955	4180.37
	49.10	103.33	72080.0	5.549E-4	988.60	115000	4180.00
5	49.70	102.83	72816.3	5.493E-4	988.36	112971	4180.54
	49.70	102.83	72820.0	5.493E-4	988.40	113000	4181.00
acc		20.0	dh	4.0	whs	2.000	
		20.0		4.0		2.000	

Table 7. Left side of fuel plate #1

jz	Tsurf	Tox-cd	Tcd-zr	Tzr-f	Tfmax	xkcp	prp4p	hcool	qc
1	100.70	125.70	138.20	163.20	175.70	0.6401	1.6943	4682.8	25.00
	100.74	125.74	138.24	163.24	175.74	0.6401	1.6930	4679.0	25.00
2	101.04	126.04	138.54	163.54	176.04	0.6408	1.6866	4705.5	25.00
	101.08	126.08	138.58	163.58	176.08	0.6408	1.6850	4702.0	25.00
3	101.38	126.38	138.88	163.88	176.38	0.6416	1.6789	4728.1	25.00
	101.42	126.42	138.92	163.92	176.42	0.6416	1.6780	4724.0	25.00
4	101.73	126.73	139.23	164.23	176.73	0.6423	1.6714	4750.7	25.00
	101.77	126.77	139.27	164.27	176.77	0.6423	1.6700	4747.0	25.00
5	102.08	127.08	139.58	164.58	177.08	0.6430	1.6639	4773.2	25.00
	102.12	127.12	139.62	164.62	177.12	0.6430	1.6630	4769.0	25.00

4.3.2 Capability 3B - Bypass option

The maximum relative difference between code and hand calculations of all parameters in this test case is 0.09%. This includes the bypass flowrates obtained with the code and hand calculations of 21.58 and 21.60 kg/s, respectively.

Table 8. Channel #1

jz	tcoola	tsata	reya	vsca	rhocol	pcool	cpa
1	49.25	104.81	86720.2	5.535E-4	988.54	120996	4180.42
	49.25	104.81	86720.0	5.535E-4	988.50	121000	4180.00
2	49.75	104.33	87453.0	5.489E-4	988.32	118993	4180.56
	49.75	104.33	87450.0	5.489E-4	988.30	119000	4181.00
3	50.25	103.83	88187.8	5.443E-4	988.09	116991	4180.70
	50.25	103.83	88190.0	5.443E-4	988.10	117000	4181.00
4	50.75	103.34	88924.7	5.398E-4	987.87	114990	4180.85
	50.75	103.34	88920.0	5.398E-4	987.90	115000	4181.00
5	51.25	102.83	89663.5	5.353E-4	987.64	112989	4181.01
	51.25	102.83	89660.0	5.353E-4	987.60	113000	4181.00
acc		20.0	dh		4.0	whe	2.400
		20.0			4.0		2.400

Table 9. Left side of fuel plate #1

jz	Tsurf	Tox-cd	Tcd-zr	Tzr-f	Tfmax	xkcp	prp4p	hcool	qc
1	94.68	119.68	132.18	157.18	169.68	0.6425	1.6695	5503.2	25.00
	94.72	119.72	132.22	157.22	169.72	0.6425	1.6680	5499.0	25.00
2	95.00	120.00	132.50	157.50	170.00	0.6431	1.6633	5524.9	25.00
	95.04	120.04	132.54	157.54	170.04	0.6431	1.6620	5520.0	25.00
3	95.32	120.32	132.82	157.82	170.32	0.6437	1.6572	5546.6	25.00
	95.36	120.36	132.86	157.86	170.36	0.6437	1.6560	5542.0	25.00
4	95.65	120.65	133.15	158.15	170.65	0.6443	1.6511	5568.2	25.00
	95.68	120.68	133.18	158.18	170.68	0.6443	1.6500	5563.0	25.00
5	95.97	120.97	133.47	158.47	170.97	0.6448	1.6451	5589.7	25.00
	96.01	121.01	133.51	158.51	171.01	0.6448	1.6440	5585.0	25.00

4.3.3 Capability 3C - End channel

The maximum relative difference between code and hand calculations of all parameters in this test case is 0.1%.

Table 10. Channel #1

jz	tcoola	tsata	reya	vsca	rhocol	pcool	cpa
1	48.26	104.77	54928.6	5.629E-4	988.98	120811	4180.15
	48.26	104.77	54930.0	5.629E-4	989.00	120800	4180.00
2	48.78	104.29	55414.4	5.580E-4	988.75	118846	4180.29
	48.78	104.29	55410.0	5.580E-4	988.80	118800	4180.00
3	49.30	103.81	55901.7	5.531E-4	988.52	116881	4180.43
	49.30	103.81	55900.0	5.531E-4	988.50	116900	4180.00
4	49.81	103.32	56390.4	5.483E-4	988.29	114916	4180.57
	49.81	103.32	56390.0	5.483E-4	988.30	114900	4181.00
5	50.33	102.83	56880.5	5.436E-4	988.06	112952	4180.73
	50.33	102.83	56880.0	5.436E-4	988.10	113000	4181.00
acc		20.0	dh		4.0	whs	1.546
		20.0			4.0		1.546

Table 11. Channel #2

jz	tcoola	tsata	reya	vsca	rhocol	pcool	cpa
1	48.17	104.78	174102.4	5.638E-4	988.98	120837	4180.12
	48.17	104.77	174100.0	5.638E-4	989.00	120800	4180.00
2	48.49	104.30	175073.1	5.607E-4	988.84	118867	4180.21
	48.49	104.30	175100.0	5.607E-4	988.80	118800	4180.00
3	48.82	103.81	176045.6	5.576E-4	988.69	116897	4180.30
	48.82	103.81	176000.0	5.576E-4	988.70	116900	4180.00
4	49.14	103.32	177019.8	5.545E-4	988.55	114927	4180.39
	49.14	103.32	177000.0	5.545E-4	988.50	114900	4180.00
5	49.47	102.83	177995.9	5.515E-4	988.40	112958	4180.48
	49.47	102.83	178000.0	5.515E-4	988.40	113000	4180.00
acc		20.0	dh		8.0	whs	2.454
		20.0			8.0		2.454

Table 12. Left side of fuel plate #1

jz	Tsurf	Tox-cd	Tcd-zr	Tzr-f	Tfmax	xkcp	prp4p	hcool	qc
1	91.66	108.33	116.66	133.33	141.66	0.6413	1.6820	3840.5	16.67
	91.70	108.36	116.70	133.36	141.70	0.6413	1.6810	3837.0	16.67
2	92.00	108.67	117.00	133.67	142.00	0.6419	1.6755	3856.3	16.67
	92.03	108.70	117.03	133.70	142.03	0.6419	1.6740	3853.0	16.67
3	92.34	109.00	117.34	134.00	142.34	0.6425	1.6690	3872.2	16.67
	92.37	109.04	117.37	134.04	142.37	0.6425	1.6680	3869.0	16.67
4	92.68	109.35	117.68	134.35	142.68	0.6431	1.6626	3888.0	16.67
	92.71	109.38	117.71	134.38	142.71	0.6431	1.6610	3885.0	16.67
5	93.02	109.69	118.02	134.69	143.02	0.6438	1.6562	3903.7	16.67
	93.06	109.72	118.06	134.72	143.06	0.6438	1.6550	3900.0	16.67

Table 13. Right side of fuel plate #1

jz	Tsurf	Tcd-ox	Tzr-cd	Tf-zr	Tfmax	xkcp	prp4p	hcool	qc
1	82.64	99.31	107.64	124.31	132.64	0.6412	1.6832	4835.0	16.67
	82.67	99.33	107.67	124.33	132.67	0.6412	1.6820	4831.0	16.67
2	82.88	99.54	107.88	124.54	132.88	0.6416	1.6791	4847.6	16.67
	82.90	99.57	107.90	124.57	132.90	0.6416	1.6780	4844.0	16.67
3	83.11	99.78	108.11	124.78	133.11	0.6420	1.6750	4860.2	16.67
	83.14	99.81	108.14	124.81	133.14	0.6420	1.6740	4856.0	16.67
4	83.35	100.01	108.35	125.01	133.35	0.6423	1.6709	4872.7	16.67
	83.38	100.04	108.38	125.04	133.38	0.6423	1.6700	4869.0	16.67
5	83.58	100.25	108.58	125.25	133.58	0.6427	1.6668	4885.3	16.67
	83.61	100.28	108.61	125.28	133.61	0.6427	1.6650	4881.0	16.67

4.3.4 Capability 3D - Fin option

The maximum relative difference between code and hand calculations of all parameters in this test case is 0.09%.

Table 14. Channel #1

jz	tcoola	tsata	reya	vsca	rhocol	pcool	cpa
1	47.31	104.85	34950.7	5.722E-4	989.41	121161	4179.91
	47.31	104.85	34950.0	5.722E-4	989.40	121200	4180.00
2	47.91	104.35	35313.2	5.664E-4	989.15	119125	4180.06
	47.91	104.36	35310.0	5.664E-4	989.20	119100	4180.00
3	48.50	103.85	35676.9	5.606E-4	988.89	117090	4180.21
	48.50	103.86	35680.0	5.606E-4	988.90	117100	4180.00
4	49.10	103.35	36041.9	5.549E-4	988.63	115056	4180.37
	49.10	103.35	36040.0	5.549E-4	988.60	115100	4180.00
5	49.70	102.83	36408.2	5.493E-4	988.36	113022	4180.54
	49.70	102.83	36410.0	5.493E-4	988.40	113000	4181.00
acc		21.0	dh		2.10	whs	2.000
		21.0			2.10		2.000

Table 15. Left side of fuel plate #1

jz	Tsurf	Tox-cd	Tcd-zr	Tzr-f	Tfmax	xkcp	prp4p	hcool	qc
1	75.35	83.68	96.18	121.18	133.68	0.6401	1.6943	2972.2	8.33
	75.37	83.70	96.20	121.20	133.70	0.6401	1.6930	2970.0	8.33
2	75.81	84.14	96.64	121.64	134.14	0.6408	1.6866	2986.6	8.33
	75.83	84.16	96.66	121.66	134.16	0.6408	1.6850	2984.0	8.33
3	76.27	84.61	97.11	122.11	134.61	0.6416	1.6789	3001.0	8.33
	76.30	84.63	97.13	122.13	134.63	0.6416	1.6780	2999.0	8.33
4	76.74	85.07	97.57	122.57	135.07	0.6423	1.6714	3015.3	8.33
	76.76	85.10	97.60	122.60	135.10	0.6423	1.6700	3013.0	8.33
5	77.21	85.54	98.04	123.04	135.54	0.6430	1.6639	3029.6	8.33
	77.23	85.56	98.06	123.06	135.56	0.6430	1.6630	3027.0	8.33

4.3.5 Capability 3E - Viscosity effect on flow rate

The maximum relative difference between code and hand calculations of all parameters in this test case is 0.11%.

Table 16. Channel #1

jz	tcoola	tsata	reya	vsca	rhocol	pcool	cpa	
1	46.31	104.79	68633.5	5.823E-4	989.84	120912	4179.68	
	46.31	104.79	68630.0	5.823E-4	989.80	120900	4180.00	
2	46.91	104.31	69354.3	5.762E-4	989.58	118926	4179.81	
	46.91	104.31	69350.0	5.762E-4	989.60	118900	4180.00	
3	47.51	103.82	70077.7	5.703E-4	989.33	116941	4179.96	
	47.51	103.82	70080.0	5.703E-4	989.30	116900	4180.00	
4	48.11	103.33	70803.5	5.644E-4	989.07	114956	4180.11	
	48.11	103.33	70800.0	5.644E-4	989.10	115000	4180.00	
5	48.71	102.83	71531.9	5.587E-4	988.80	112972	4180.27	
	48.71	102.83	71530.0	5.587E-4	988.80	113000	4180.00	
acc		20.0	dh		4.0	whs		1.998
		20.0			4.0			1.998

Table 17. Channel #2

jz	tcoola	tsata	reya	vsca	rhocol	pcool	cpa
1	46.61	104.79	69187.2	5.792E-4	989.84	120912	4179.75
	46.61	104.79	69190.0	5.792E-4	989.80	120900	4180.00
2	47.80	104.31	70633.9	5.674E-4	989.33	118926	4180.03
	47.80	104.31	70630.0	5.674E-4	989.30	118900	4180.00
3	49.00	103.82	72090.5	5.559E-4	988.81	116940	4180.34
	49.00	103.82	72090.0	5.559E-4	988.80	116900	4180.00
4	50.19	103.33	73557.1	5.448E-4	988.27	114955	4180.69
	50.19	103.33	73560.0	5.448E-4	988.30	115000	4181.00
5	51.39	102.83	75033.3	5.341E-4	987.73	112970	4181.05
	51.39	102.83	75030.0	5.341E-4	987.70	113000	4181.00
acc		20.0	dh	4.0	whs	2.004	
		20.0		4.0		2.004	

Table 18. Left side of fuel plate #1

jz	Tsurf	Tcd-f	Tfmax	xkcp	prp4p	hcool	qc
1	100.18	112.68	125.18	0.6389	1.7074	4641.3	25.00
	100.21	112.71	125.21	0.6389	1.7060	4638.0	25.00
2	100.51	113.01	125.51	0.6396	1.6995	4664.1	25.00
	100.55	113.05	125.55	0.6396	1.6980	4661.0	25.00
3	100.85	113.35	125.85	0.6404	1.6917	4686.8	25.00
	100.89	113.39	125.89	0.6404	1.6900	4683.0	25.00
4	101.19	113.69	126.19	0.6411	1.6840	4709.5	25.00
	101.23	113.73	126.23	0.6411	1.6830	4706.0	25.00
5	101.54	114.04	126.54	0.6418	1.6764	4732.1	25.00
	101.58	114.08	126.58	0.6418	1.6750	4728.0	25.00

Table 19. Right side of fuel plate #1

jz	Tsurf	Tcd-f	Tfmax	xkcp	prp4p	hcool	qc
1	100.22	112.72	125.22	0.6392	1.7035	4663.2	25.00
	100.26	112.76	125.26	0.6392	1.7020	4660.0	25.00
2	100.90	113.40	125.90	0.6407	1.6879	4708.6	25.00
	100.94	113.44	125.94	0.6407	1.6870	4705.0	25.00
3	101.59	114.09	126.59	0.6422	1.6727	4753.9	25.00
	101.63	114.13	126.63	0.6422	1.6710	4750.0	25.00
4	102.29	114.79	127.29	0.6436	1.6579	4798.8	25.00
	102.33	114.83	127.33	0.6436	1.6560	4795.0	25.00
5	103.00	115.50	128.00	0.6450	1.6434	4843.6	25.00
	103.04	115.54	128.04	0.6450	1.6420	4839.0	25.00

4.3.6 Capability 3F - Power split calculation

The maximum relative difference between code and hand calculations of all parameters in this test case is 0.11%.

Table 20. Channel #1

jz	tcoola	tsata	reya	vsca	rhocol	pcool	cpa
1	45.39	106.95	90123.9	5.918E-4	990.26	131180	4179.48
	45.39	106.95	90120.0	5.918E-4	990.30	131200	4179.00
2	46.14	106.02	91323.3	5.840E-4	989.94	127139	4179.64
	46.14	106.02	91320.0	5.840E-4	989.90	127100	4180.00
3	46.89	105.07	92532.2	5.764E-4	989.62	123100	4179.81
	46.89	105.07	92530.0	5.764E-4	989.60	123100	4180.00
4	47.65	104.09	93750.8	5.689E-4	989.30	119061	4179.99
	47.65	104.09	93750.0	5.689E-4	989.30	119100	4180.00
5	48.41	103.09	94979.1	5.615E-4	988.97	115024	4180.19
	48.41	103.09	94980.0	5.615E-4	989.00	115000	4180.00
acc		20.0	dh	4.0	whs	2.667	
		20.0		4.0		2.667	

Table 21. Channel #2

jz	tcoola	tsata	reya	vsca	rhocol	pcool	cpa
1	45.76	106.94	90718.9	5.879E-4	990.26	131165	4179.56
	45.76	106.94	90720.0	5.879E-4	990.30	131200	4180.00
2	47.26	106.02	93116.0	5.728E-4	989.63	127125	4179.90
	47.25	106.02	93110.0	5.728E-4	989.60	127100	4180.00
3	48.75	105.07	95530.0	5.583E-4	988.98	123087	4180.28
	48.74	105.07	95520.0	5.584E-4	989.00	123100	4180.00
4	50.23	104.09	97960.1	5.444E-4	988.32	119052	4180.70
	50.22	104.09	97930.0	5.446E-4	988.30	119100	4181.00
5	51.72	103.09	100405.7	5.312E-4	987.65	115019	4181.16
	51.69	103.09	100400.0	5.314E-4	987.70	115000	4181.00
acc		20.0	dh	4.0	whs	2.667	
		20.0		4.0		2.667	

Table 22. Left side of fuel plate #1

jz	Tsurf	Tcd-f	Tfmax	xkcp	prp4p	hcool	qc	fp
1	81.35	102.22	112.68	0.6377	1.7198	5802.5	20.87	0.501
	81.38	102.25	112.70	0.6377	1.7190	5799.0	20.87	0.501
2	82.01	102.95	113.47	0.6386	1.7097	5838.6	20.94	0.503
	82.03	102.97	113.49	0.6386	1.7080	5835.0	20.94	0.503
3	82.66	103.68	114.27	0.6396	1.6997	5874.7	21.01	0.504
	82.69	103.70	114.30	0.6396	1.6980	5870.0	21.01	0.504
4	83.32	104.41	115.08	0.6405	1.6899	5910.9	21.09	0.506
	83.35	104.44	115.11	0.6405	1.6890	5906.0	21.09	0.506
5	83.99	105.16	115.90	0.6415	1.6802	5947.0	21.16	0.508
	84.02	105.18	115.92	0.6415	1.6790	5942.0	21.16	0.508

Table 23. Right side of fuel plate #1

jz	Tsurf	Tcd-f	Tfmax	xkcp	prp4p	hcool	qc	fp
1	81.50	102.29	112.68	0.6382	1.7147	5820.5	20.80	0.499
	81.52	102.32	112.70	0.6382	1.7140	5816.0	20.80	0.499
2	82.43	103.16	113.47	0.6400	1.6950	5892.1	20.73	0.497
	82.46	103.18	113.49	0.6400	1.6940	5888.0	20.73	0.497
3	83.38	104.03	114.27	0.6419	1.6759	5963.1	20.65	0.496
	83.40	104.06	114.30	0.6419	1.6750	5958.0	20.65	0.496
4	84.34	104.92	115.08	0.6436	1.6574	6033.6	20.58	0.494
	84.36	104.94	115.11	0.6436	1.6560	6028.0	20.58	0.494
5	85.31	105.82	115.90	0.6454	1.6394	6103.5	20.50	0.492
	85.32	105.83	115.92	0.6453	1.6380	6097.0	20.51	0.492

4.3.7 Capability 3G - ONB temperature

The core power of the base model is increased so that the ONB is detected at two axial nodes. The obtained temperature profiles and the list of these ONB nodes are provided in Table 24.

The maximum relative difference between the temperatures obtained by code and hand calculation in this test case is 0.05%.

Table 24. Temperature profiles of channel #1 and left side of plate #1

jz	Tcoola	Tsata	Tonb	Tsurf	Tox-cd	Tcd-zr	Tzr-f	Tfmax	ONB
1	46.86	104.81	111.61	109.37	138.54	153.12	182.29	196.87	No
	46.86	104.79	111.63	109.42	138.58	153.17	182.33	196.92	No
2	47.56	104.33	111.18	109.72	138.88	153.47	182.63	197.22	No
	47.56	104.31	111.20	109.76	138.93	153.51	182.68	197.26	No
3	48.26	103.83	110.75	110.07	139.23	153.82	182.98	197.57	No
	48.26	103.82	110.77	110.12	139.28	153.87	183.03	197.62	No
4	48.95	103.34	110.31	110.42	139.59	154.17	183.34	197.92	Yes
	48.95	103.33	110.33	110.47	139.64	154.22	183.39	197.97	Yes
5	49.65	102.83	109.86	110.78	139.95	154.53	183.70	198.28	Yes
	49.65	102.83	109.89	110.83	140.00	154.58	183.75	198.33	Yes

4.4 Comparison between STAT7 and PLTEMP calculations

As mentioned in Section 3.4, the comparison between STAT7 and PLTEMP codes is performed by matching the total core flowrate of the test models (Figure 2). It can be seen in Figure 3 and Figure 4 that the temperatures calculated by the codes agree very well to each other.

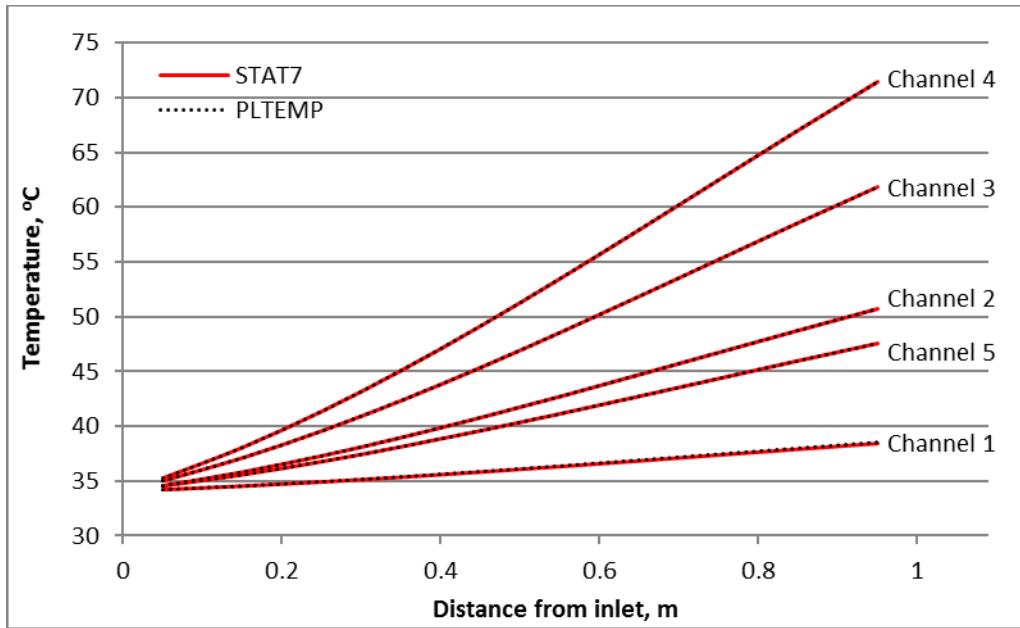


Figure 3. Coolant temperature profiles

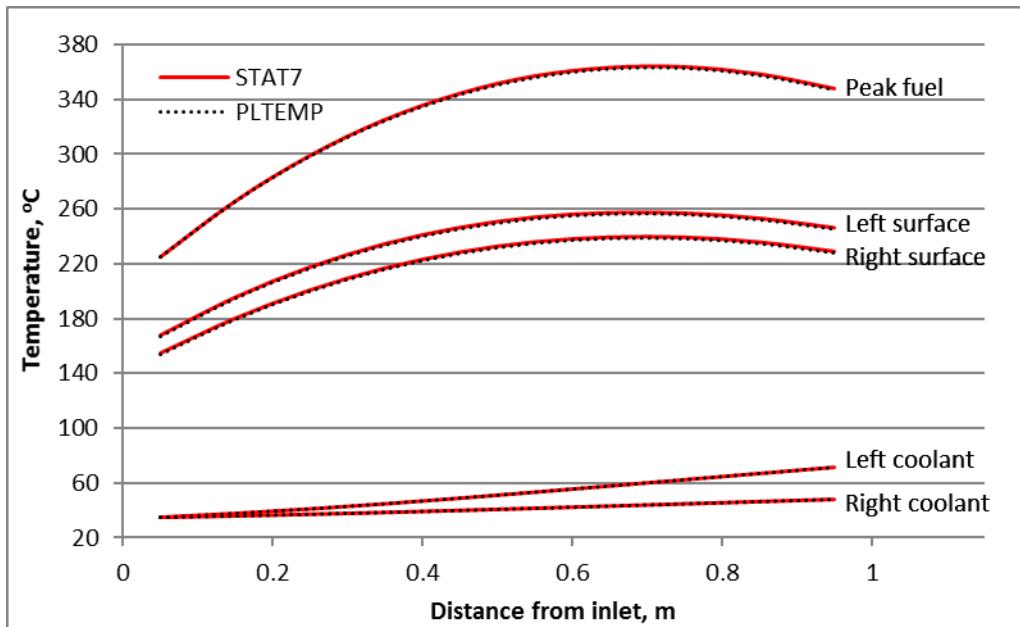


Figure 4. Temperature profiles corresponding to fuel plate #4

The comprehensive comparisons including all thermal hydraulic parameters are performed using node-to-node comparison for all channels. It should be noticed that the codes used different generators for coolant properties. Consequently, the coolant properties show differences up to 0.73% (Table 25) which could be responsible for the differences in other data. Nevertheless, a good agreement within 0.75% is achieved for all thermal hydraulic parameters belonging to the fuel core region as can be seen in Table 26.

The obtained bypass flowrates, however, present a difference of 3.1%, which does indicate an issue in the STAT7 calculations if this particular thermal hydraulics capability would be utilized (it has not been utilized to date). As an attempt to investigate this problem, the existing test models (Figure 2) are rerun without the fins. The results included in Table 26 show a good agreement between the bypass flowrates calculated by the codes when the fins have been removed. Therefore, it can be concluded that the bypass flowrate is calculated correctly if the fuel plates do not have fins, and incorrectly if fins are present.

It should also be clarified that both existing and prospective applications of STAT7 code in the steady-state thermal-hydraulic analyses at MIT Reactor do not use bypass capability in the same way of current test models. Instead of letting the code calculate bypass flowrate, these analyses have been specifying the flow distribution in the core region and the bypass channel as an input parameter named "coolant flow factor". In the other words, although the issue of bypass flowrate calculation with the present of fins will need to be resolved, it does not affect the application of STAT7 in the thermal hydraulic analyses performed to date and will be noted as a limitation of the code until corrected.

Table 25. Node-to-node comparison of coolant properties reported by STAT7 and PLTEMP

Channel	Max. relative difference, %		
	Viscosity	Thermal Conductivity	Density
1	0.05	0.73	0.02
2	0.66	0.50	0.05
3	0.67	0.44	0.06
4	0.59	0.50	0.07
5	0.55	0.54	0.04

Table 26. Comparison of thermal hydraulic data obtained with STAT7 and PLTEMP

Thermal hydraulic parameters		Max. relative difference, %	
		Test models (Figure 2)	Test models without fins
Node-to-node comparison for all channels	Coolant temperature	0.05	0.05
	Cladding temperature	0.48	0.53
	Fuel peak temperature	0.35	0.41
	ONB temperature	0.06	0.08
	HT coefficient	0.75	0.08
	Heat flux	0.21	0.71
	Pressure	0.04	0.21
Flow rates	Core region	Channel 1	0.06
		Channel 2	0.05
		Channel 3	0.08
		Channel 4	0.09
		Channel 5	0.03
	Bypass channel	3.10	0.11

5 Conclusions

The data and discussions presented above lead to the following conclusions:

- The random number generator embedded in the code is suitable to be used for the statistical sampling.
- The coolant properties generated by the code agree well with data provided by NIST tables within the relative difference of 0.11%.
- The key thermal hydraulic capabilities are verified independently using hand calculations. The relative differences between the code and hand calculation are less than 0.12% for all test cases.
- The comprehensive comparison between the STAT7 and PLTEMP using a five-channel test-problem involving all thermal hydraulic capabilities is performed. The obtained data show that the codes agree well with each other within 0.75% for all thermal hydraulic parameters belonging to the core region.
- The difference of 3.1% in bypass flowrate indicates an issue with STAT7 calculations when both fin and bypass capabilities are involved. This problem, however, does not affect the application of the code in the manner utilized to date where the flow distribution in core region and bypass channel is specified as an input parameter.

Acknowledgement

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References

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- [3] A.P. Olson, M. Kalimullah, and E. Feldman. A User's Guide to the PLTEMP/ANL Code, ANL/RERTR/TM-11-22 Rev. 2, Version 4.2 (July 25, 2016).
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Appendix: STAT7 and PLTEMP Input Files

STAT7 Input

```

Test problem: 5 channels, 4 finned fuel plates, 1 non fuel plate
  nelm | nplt | nstrp |    nz |nbatch | nsmpl |   isd1 |   isd2 |   iprt |idbstt |
      1   |    4   |     1   |    10  |       1   |       1   |     21  |       3   |     10  |       1
  nchan |iaxpow |irndmn |   ipow |iterpw | iend1 | iendn |  ivsc | niter | ilocp |
      5   |     0   |     0   |     0   |     0   |     1   |     0   |     0   |     10  |       1
  ipwshp |ifat1 |iflwnc |   idf |itrprt | inom |ipronb |libypas |ivscfl | ioptn |
      2   |     0   |     0   |     0   |     3   |     1   |     5   |     1   | 10002
  thdbug |  fcore |  ffuel | flwfac |      df | flwinc |   pow0 |   powsgm | cnveps |
      0   | 1.00000 | 1.00000 | 0.01000 | 1.00000 | 1.00000 | 2.00000 | 0.00000 | 0.05000
  plocsg | sigmax |   tout |    wp0 |   wpsgm | coolht |      f1 |      fw | thzrml |   xkzr
  |
  0.00000 | 8.00000 | 50.00000 | 30.00000 | 0.00000 | 0.00000 | 1.00000 | 0.40000 | 0.00000 | 20.00000
  grvdml | grvwml | grvtml |  gapml |  gapsg | grvfav | htcsgm | epsonb | thkoxm |   xkox
  |
  78.74016 | 78.74016 | 78.74016 | 629.92126 | 0.00000 | 0.50000 | 0.00000 | 0.00000 | 0.00000 | 10.00000
  gapml0 | flstrf | acbyp | dhbyp | afrv | xke | bfrv | xkf | fcarff |
  629.92126 | 1.00000 | 0.00500 | 0.05000 | 0.18400 | 100.00000 | -0.20000 | 50.00000 | 1.00000
  ich | gapmli | gapsgi | gapmla |
  1 | 708.66 | 0.00000 | 708.66
  2 | 629.92 | 0.00000 | 629.92
  3 | 629.92 | 0.00000 | 629.92
  4 | 629.92 | 0.00000 | 629.92
  5 | 708.66 | 0.00000 | 708.66
  iplate | thkf | thke |
  1 | 393.70 | 196.85
  2 | 393.70 | 196.85
  3 | 393.70 | 196.85
  4 | 393.70 | 196.85
  5 | 393.70 | 196.85
  6 | 393.70 | 196.85
  iplate | fstrp | axpow |
  1 | 0.00
  0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000
  0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000
  iplate | fstrp | axpow |
  2 | 0.40
  0.06388 | 0.07779 | 0.08949 | 0.09899 | 0.10628 | 0.11140 | 0.11420 | 0.11490
  0.11339 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965
  iplate | fstrp | axpow |
  3 | 0.80
  0.06388 | 0.07779 | 0.08949 | 0.09899 | 0.10628 | 0.11140 | 0.11420 | 0.11490
  0.11339 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965
  iplate | fstrp | axpow |
  4 | 1.20
  0.06388 | 0.07779 | 0.08949 | 0.09899 | 0.10628 | 0.11140 | 0.11420 | 0.11490
  0.11339 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965
  iplate | fstrp | axpow |
  5 | 1.60
  0.06388 | 0.07779 | 0.08949 | 0.09899 | 0.10628 | 0.11140 | 0.11420 | 0.11490
  0.11339 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965 | 0.10965
  iplate | fstrp | axpow |
  6 | 0.00
  0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000
  0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000

```

PLTEMP Input

VnV STAT7 - using Carnavos

```

! IH IB CHF FTYP 5 6 7 8 IGOM 10 11 IEND 13 14 ICHF 16 17 18 19 MORE
-1 0 0 1 1 0 1 1 0 0 0 0 0 1 0 2 1 0 0 0 Card(1)0200
! EFIN BFIN TFIN AHELIX NFIN
2.00000E-3 2.00000E-3 2.00000E-3 0.00000E+0 200 Card(1)0202
! NSRCH X-LOW X-HIGH NTARGT YTARGT
1 1.00000E-4 1.00000E-2 1 2.45775E+1 Card(1)0203
! NELF NF WFGES FB FQ FH IBC IBCA HBC
1 3 2.32184E+1 1.00000E+0 1.00000E+0 1.00000E+0 3 0 1.00000E+0 Card(1)0300
! IQNODS, IQNODF, FQL
1 11 1.00000E+0 Card(1)0301
! IEFLFH, ICHNHF, IPLTHF
1 1 1 Card(1)0302
! FZ(I,J)
1.06474E-1 Card(1)0303
! AF DF LF ZF WIDTH THICK
4.00000E-2 4.44444E-2 0.00000E+0 0.00000E+0 4.00000E-1 2.00000E-2 Card(1)0304
4.00000E-2 4.44444E-2 1.00000E+0 0.00000E+0 4.00000E-1 2.00000E-2 Card(1)0304
4.00000E-2 4.44444E-2 0.00000E+0 0.00000E+0 4.00000E-1 2.00000E-2 Card(1)0304
! FCOEF FEXPF ROUGH CHIMNY
1.84000E-1 2.00000E-1 0.00000E+0 Card(1)0305
! NCHNF, IDC UNFUEL L CLAD TCCLAD TAEM TCFUEL
5 0 0.00000E+0 1.00000E+0 5.00000E-3 1.00000E+2 1.00000E-2 5.00000E+1 Card(1)0306
! AFF DFF PERF XIF WIDTHH THICKH
8.00000E-3 4.00000E-2 8.00000E-1 4.00000E-1 4.00000E-1 2.00000E-2 Card(4)0307
8.00000E-3 4.00000E-2 8.00000E-1 8.00000E-1 4.00000E-1 2.00000E-2 Card(4)0307
8.00000E-3 4.00000E-2 8.00000E-1 8.00000E-1 4.00000E-1 2.00000E-2 Card(4)0307
8.00000E-3 4.00000E-2 8.00000E-1 8.00000E-1 4.00000E-1 2.00000E-2 Card(4)0307
8.00000E-3 8.00000E-2 4.00000E-1 4.00000E-1 4.00000E-1 2.00000E-2 Card(4)0307
! CIRCF(I,K)
4.00000E-1 4.00000E-1 4.00000E-1 4.00000E-1 0.00000E+0 0.00000E+0 Card(1)0308
! FACTF(I,J,K)
4.00000E-1 8.00000E-1 1.20000E+0 1.60000E+0 0.00000E+0 0.00000E+0 Card(1)0309
! NCRS NC WCGES
1 1 1.00000E+1 Card(1)0400
! AC DC LC ZC WIDTHC THICKC
5.00000E-3 5.00000E-2 1.00000E+0 0.00000E+0 0.00000E+0 0.00000E+0 Card(1)0401
! FCOEC FEXPC ROUGH
1.84000E-1 2.00000E-1 0.00000E+0 Card(1)0402
! DPO DDP DPMAX POWER TIN P
5.00000E-4 5.00000E-5 0.00000E+0 2.00000E+0 3.40500E+1 1.11300E-1 Card(2)0500
! QFCLAD QFCOOL EPSLN EPSLNI
0.00000E+0 0.00000E+0 Card(2)0500
! ITER CONV ETA DPWR PWRM
20 1.00000E-4 3.25000E+1 0.00000E+0 0.00000E+0 Card(1)0600
! NN
11 Card(1)0700
! ZR QVZ
0.00000E+0 5.19976E-2 Card(11)0701
1.00000E-1 6.59156E-2 Card(11)0701
2.00000E-1 7.77884E-2 Card(11)0701
3.00000E-1 8.76159E-2 Card(11)0701
4.00000E-1 9.53982E-2 Card(11)0701
5.00000E-1 1.01135E-1 Card(11)0701
6.00000E-1 1.04827E-1 Card(11)0701
7.00000E-1 1.06474E-1 Card(11)0701
8.00000E-1 1.06075E-1 Card(11)0701
9.00000E-1 1.03631E-1 Card(11)0701
1.00000E+0 9.91420E-2 Card(11)0701
0 Card(11)0702

```



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